GA Optimization for RFID Broadband Antenna Applications

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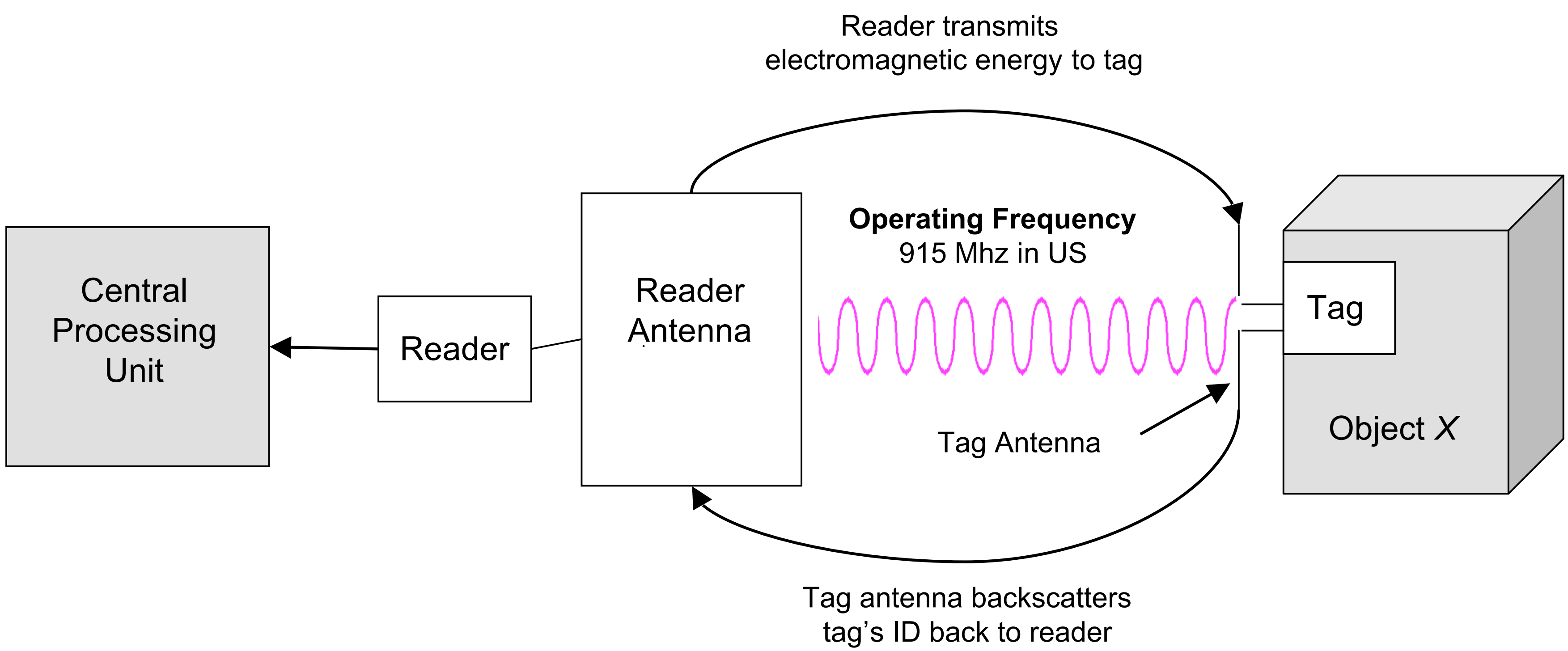
Overview

- Introduction
  - What is RFID?
  - Brief explanation of Genetic Algorithms
- Antenna Theory and Design
- Walk-through design of RFID bowtie antenna
- Genetic Algorithms
- Examples of GA-optimized antennas
- GA-optimization in RFID

Radio Frequency IDentification

- Track and trace technology
- RFID system consists of reader, tag, and processing unit
- Passive UHF RFID becoming pervasive in supply chain management
  - Tags are small and disposable
  - Items can be uniquely identified and multiple items can be simultaneously recognized

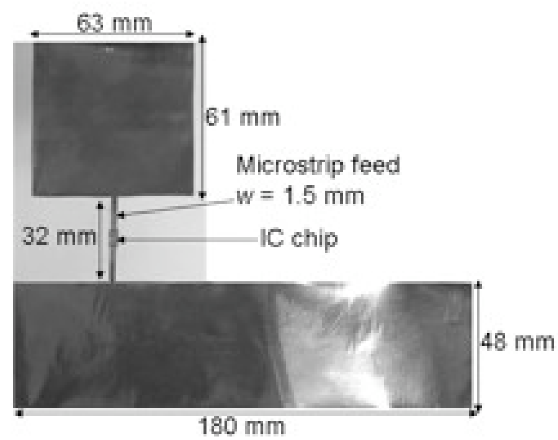
RFID System


Reader transmits
electromagnetic energy to tag
Central
Processing
Unit
Reader
Reader
Antenna
Operating Frequency
915 Mhz in US
Tag
Tag Antenna
Object X
Tag antenna backscatters
tag's ID back to reader

Challenges in RFID Tag Antenna Design

- Antennas are orientation-sensitive
- Antennas are material-sensitive
- Antennas are bandwidth limited

Albano-Dipole Antenna



Albano-Patch Antenna

General Antenna Design

- Beyond simple wire antennas, mathematical analysis becomes very complicated
- Antenna design is a mix of intuition, empirical testing, and luck
- Attempt to create “optimal” and precise antenna using traditional techniques is nearly impossible

Genetic Algorithms

- Based on biological evolutionary process of selection, crossover, and mutation
- *Global* search optimizer
- John Holland published *Adaptation in Natural and Artificial Systems,* 1975
- Used in numerous applications from code-breaking to circuit design to finance

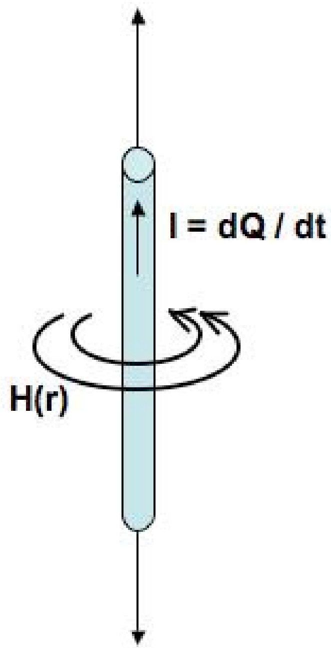
GA-optimizers for RFID antennas

- Are GA-optimizers better suited than for RFID antenna design than existing techniques?
- In other words, can they offer something existing methods can not?

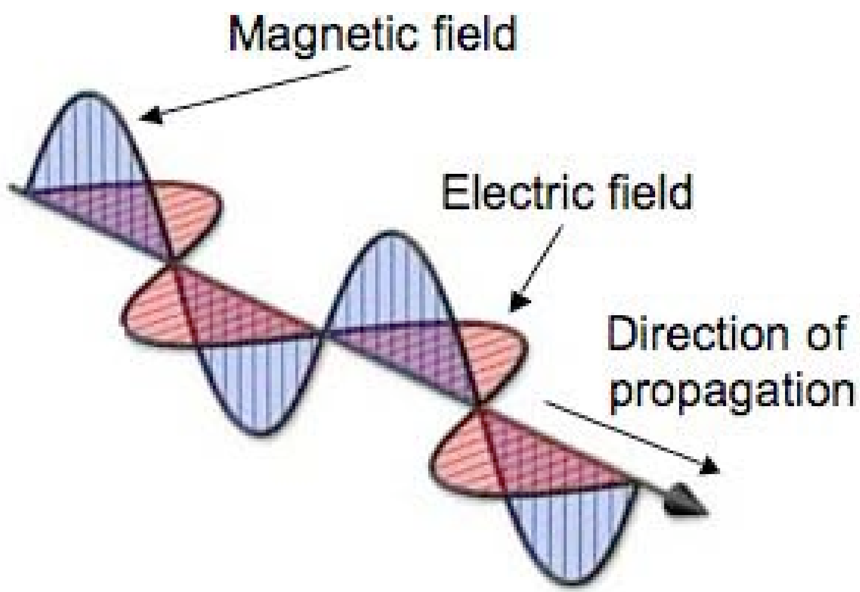
Antenna Theory

- An antenna is a "transition device, or transducer, between a guided wave and a free-space wave, or vice-versa"
- Current-carrying element or *antenna* creates a time-varying magnetic field which then creates a time-varying electric field and so forth to generate a free-space electromagnetic wave

Antenna Theory



A current-carrying wire creates a magnetic field that circles the wire in accordance with the right-hand rule



A time-varying electric field and a time-varying magnetic field that are coupled and orthogonal to each other, creating a electromagnetic wave.

Gain

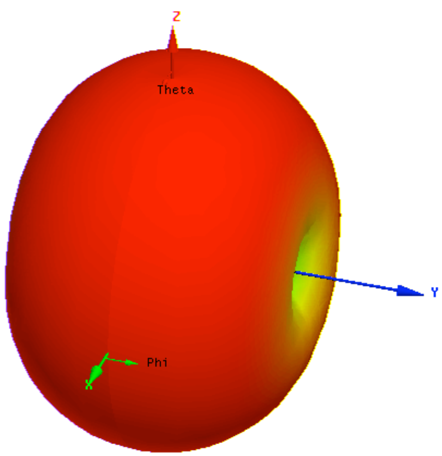
- Ratio of maximum power density to its average value over a sphere
- Often expressed in dBi, I for isotropic
- Isotropic antenna radiates equally in all directions; gain is 1 dBi
- Common half-wave dipole has gain of 2.15 dBi
- High-gain antennas gains ~20dBi

Resonant Frequency

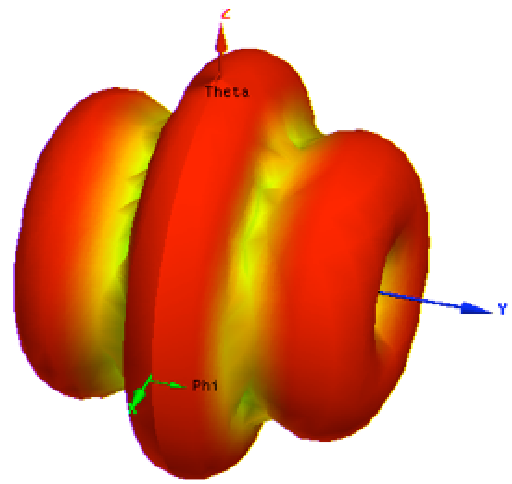
- Most UHF antennas are resonant antennas and “resonate” or operate at a particular frequency
- Sized proportionally to wavelength of operating wave
- Half-wave dipole at 915 Mhz has length of 15 cm, approx. $\lambda/2$

Radiation Pattern

- Graphical representation of antenna's power density in space



Half-wave dipole

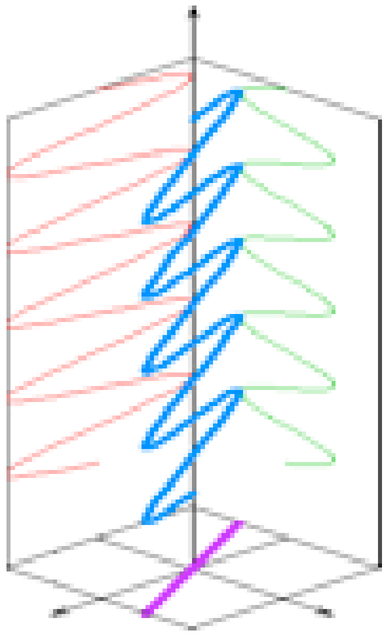


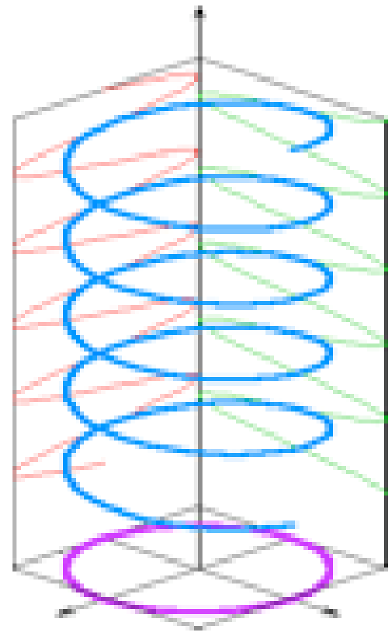
5/4λ dipole

Polarization

- Magnitude and phase of electric-field components determine antenna’s polarization
- Linear and Circular Polarization
- E-fields of two linearly-polarized antennas must be aligned for communication
- Circular antenna is orientation-insensitive but linear antenna radiates higher power

Polarization





The electric field components of a linearly-polarized wave project a line onto a plane and those of a circularly-polarized wave project a circle.

Input Impedance

- Ratio of voltage to current at antenna's terminals
- Impedance Z has real portion, radiation resistance R_{rad} and ohmic losses R_{ohmic}, and reactive portion X contains energy from fields surrounding antenna:

$$Z = R_{rad} + R_{ohmic} + jX$$

Impedance Matching

- For maximum power transfer between antenna and its attached load, the impedances of the antenna and the load must be conjugate matches
- Reflection coefficient *Γ* is a measure of how much of the transferred energy is reflected back into the original source:

$$|\Gamma| = \frac{Z_l - Z_a}{Z_l + Z_a}$$

$$\Gamma = 1 \,|\, Z_l = 0, \propto$$

All energy is reflected back into antenna

$$\Gamma = 0 \,|\, Z_l = Z_a$$

All energy is absorbed by microchip

Voltage Standing Wave Ratio

- Ratio of reflected voltage over incident voltage:

$$VSWR = \frac{1 + \Gamma}{1 - \Gamma}$$

- VSWR of 1 is desirable desirable because no energy is reflected or "lost" from the load back into the antenna.

Bandwidth

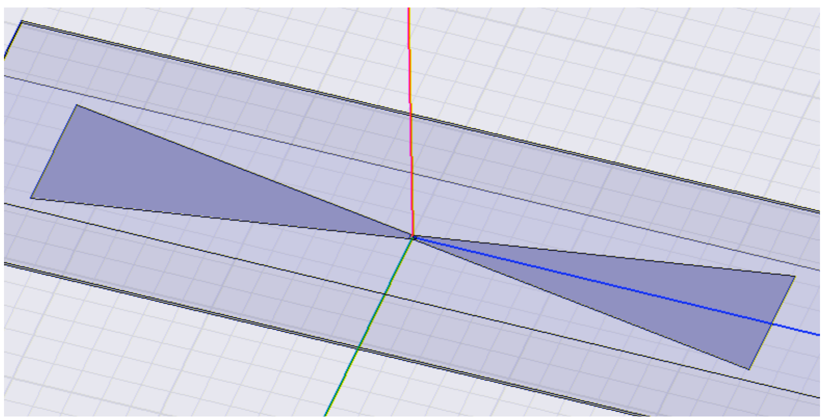
- *Half-power bandwidth* is the range of frequencies around the resonant frequency at which the system is operating with at least half of its peak power
- More common in antenna design is *Impedance bandwidth*-- specified as the range of frequencies over which the VSWR is less than 2 which translates to an 11% power

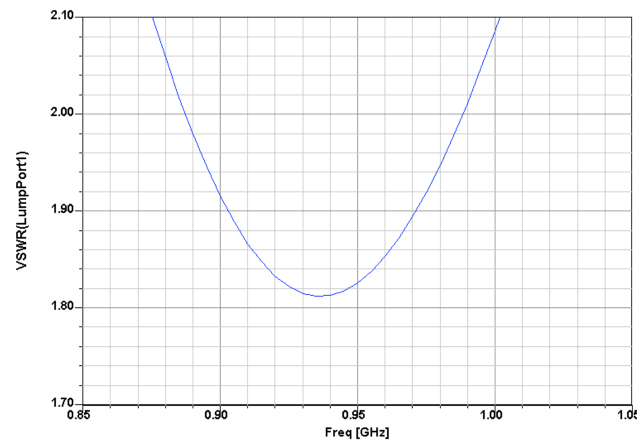
RFID Bowtie Antenna

- Bandwidth from 860 Mhz - 960 Mhz
- Size comparable to Avery Dennison's (5.5in x .98 in) bowtie antenna
- Minimal copper
- High impedance to match microchip's impedance of 1200-145j Ω
- Good gain (> 2dBi)

RFID Bowtie Antenna

- Triangle height affects resonant frequency
- Triangle base affects impedance bandwidth



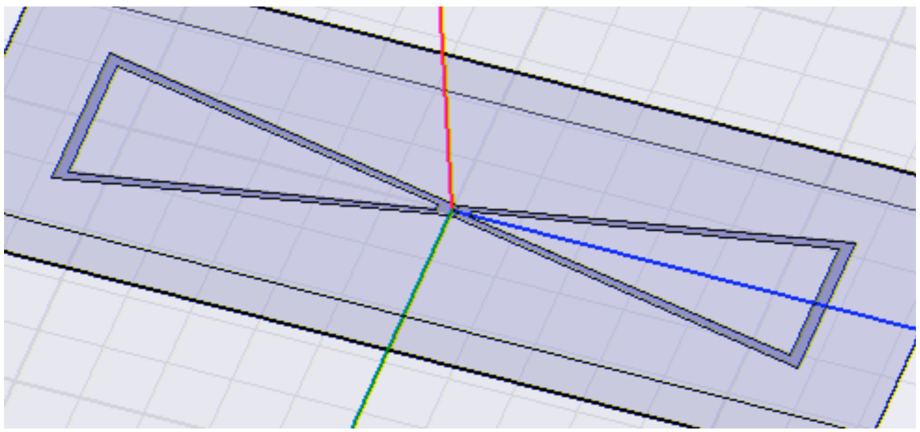


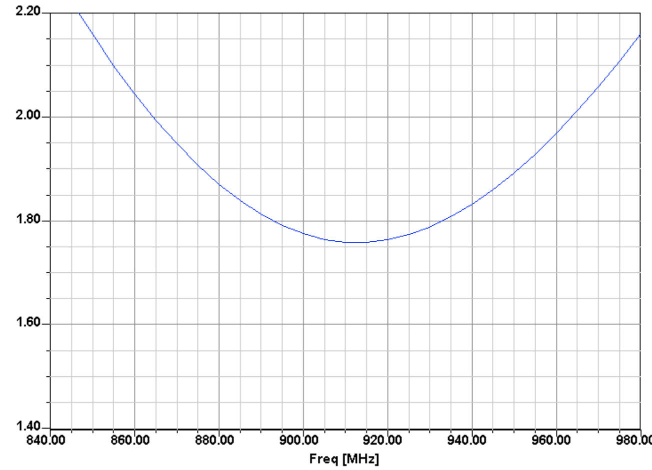
Triangle height: 120mm
Triangle base: 50 mm

Resonant Frequency: 935 Mhz
Impedancw BW: 885-980 Mhz

RFID Bowtie Antenna

Bowtie Wire Antenna



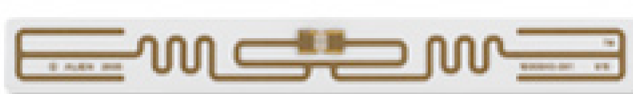


Triangle Height: 115mm
Total Dimensions: 230 mm x 50mm
(9.45 in x 1.98 in compared to AD's 5.51in x .98 in antenna)

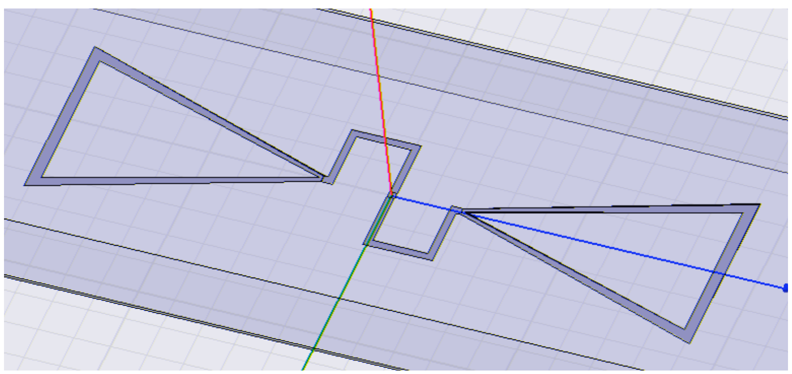
Resonant Frequency: 912 Mhz
Impedance BW: 865-965

RFID Bowtie Antenna

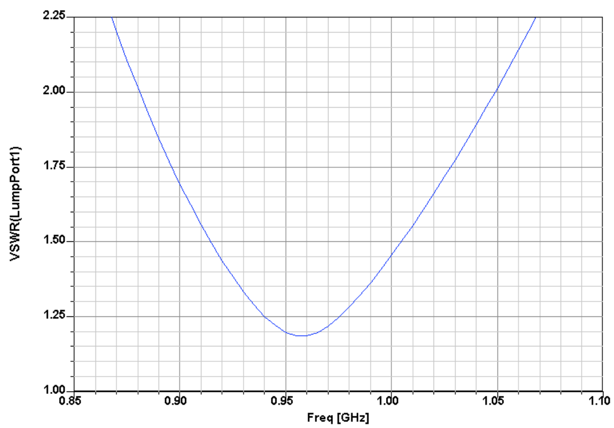
Bowtie-Wire-Squiggle Antenna



Alien Technology's "Squiggle" Tag



Total Dimensions: 180mm x 50 mm
(7.1 in x 1.98 in)



Resonant Frequency: 955 Mhz
Imepdance BW: 880 - 1050 Mhz

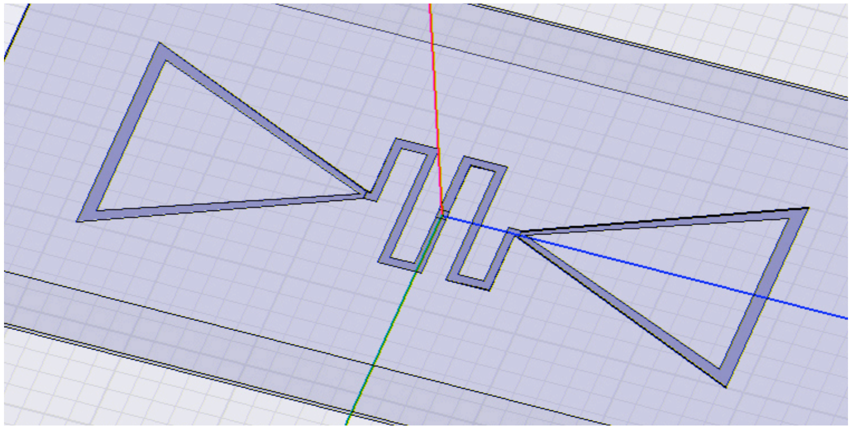
RFID Bowtie Antenna

Bowtie-Wire-Double-Squiggle Antenna

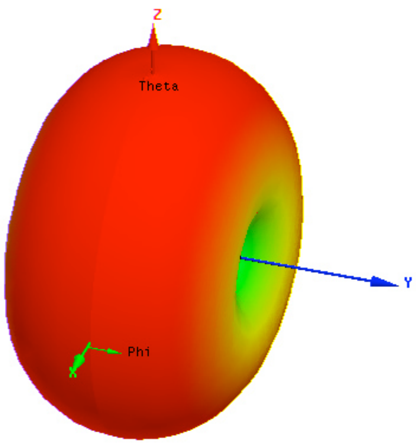
Dimensions:

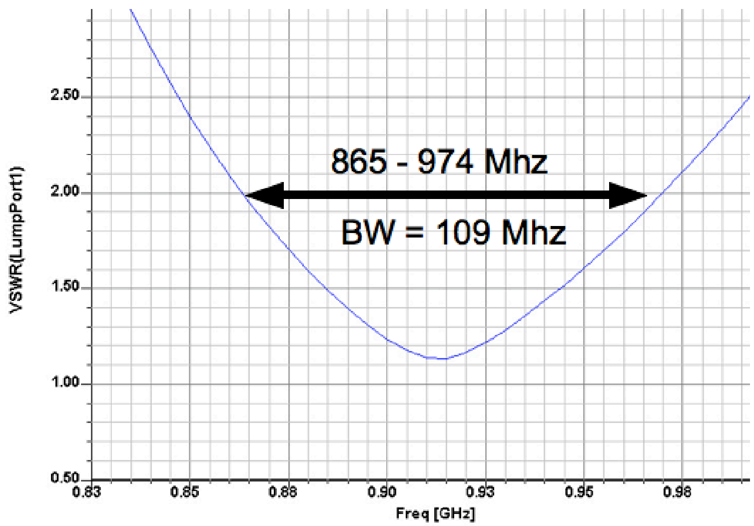
136mm x 50 mm

(5.35 in x 1.98 in)



Gain: 2.735 dBi
R.F.: 915 Mhz
Impedance BW:
865 – 974 Mhz



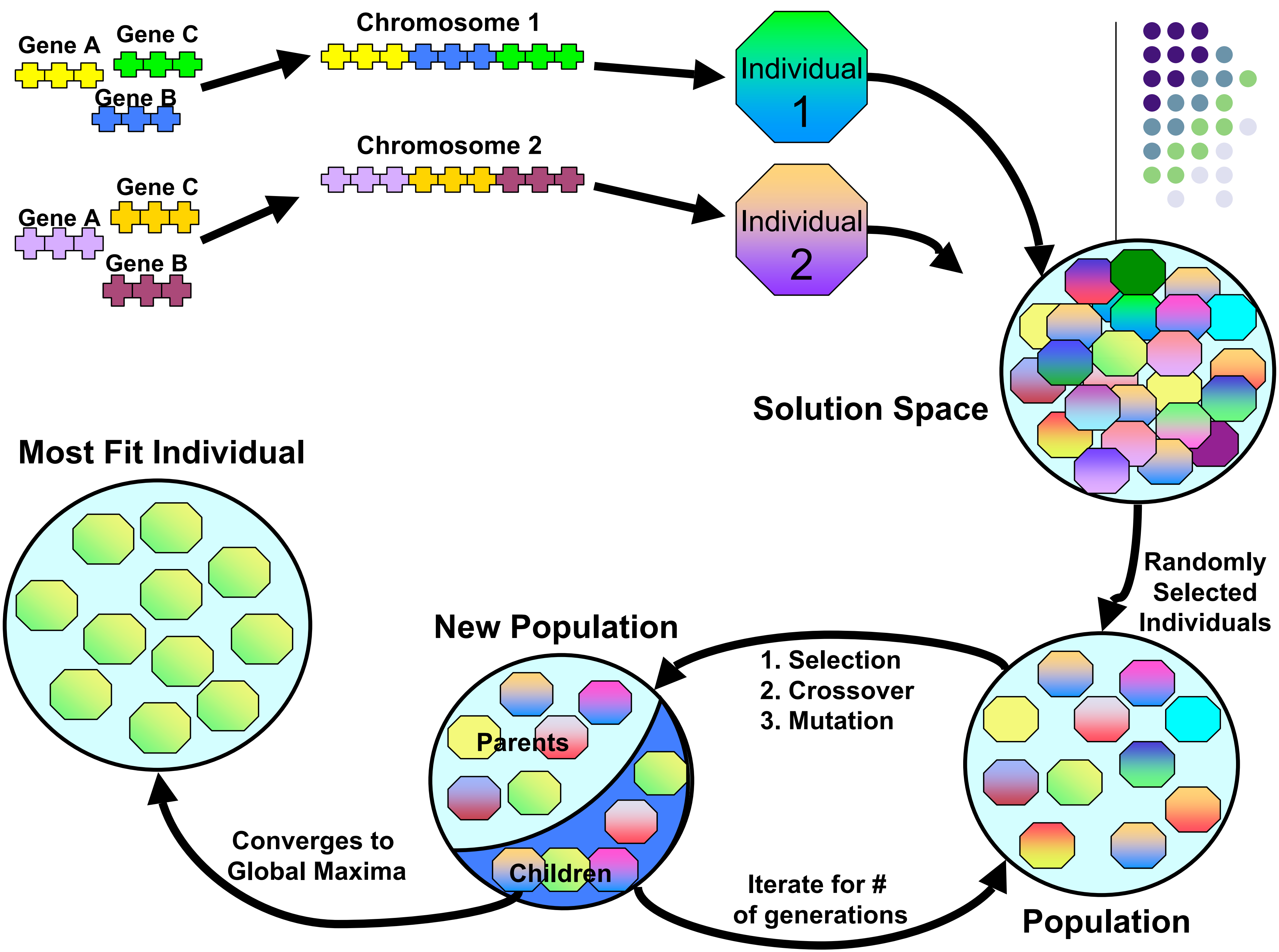


Discussion of Design

- Clearly a hand-wavy result of intuition, several antenna techniques, and experimentation
- Could a more optimal antenna be designed using genetic algorithms?
- Is antenna design a good candidate for a genetic algorithm optimizer?

Genetic Algorithm

- Search and optimization technique inspired by nature's evolutionary processes
- A population of candidates iterates through multiple generations of selection, crossover, and mutation until an optimized solution survives, much in the manner of "survival of the fittest".


Gene A
Gene C
Gene B
Chromosome 1
Individual 1
Chromosome 2
Gene C
Gene A
Gene B
Individual 2
Solution Space
Most Fit Individual
Randomly Selected Individuals
New Population
1. Selection
2. Crossover
3. Mutation
Parents
Children
Converges to Global Maxima
Iterate for # of generations
Population

Individuals

- Also known as *chromosome,* is the candidate solution to the problem at hand
- Comprised of parameters or “genes”
- Genes are often binary-mapped
- If a chromosome made up of three genes that were 4 bits long each, there would be 2^{12} possible solutions -- *Solution Space*

Population and Fitness Function

- Defined number of randomly generated individuals establish initial *population* of possible solutions
- Fitness function enumerates how "fit" an individual is
  - A fitness function for an antenna could scale and combine the antenna's gain and VSWR for instance
  - Produces *one* number that encompasses combined rating of individual's genes

Selection

- Population Decimation
- Proportional Selection/ Roulette Wheel Selection
- Tournament Selection

Population Decimation

- Individuals are ranked according to fitness rating and cutoff point decimates weakest individuals
- Immediate loss of diversification in the next generation population

Proportional Selection

- Selects individuals with a probability that is proportional to their ratings
- Allows weak individuals a chance to continue through to next generation and thus maintains diversity

Tournament Selection

- Converges faster than Proportional Selection does
- Sub-population of individuals is randomly chosen to compete on the basis of their fitness
- Individuals with the highest fitness win the competition and continue to the next generation
- Other individuals are placed back into the general population and the process is repeated until a desired number of individuals have “won”

Crossover

- Object is to create better combination of genes--> more fit individuals
- Applied with probably .6-.8 in most cases
- Random location in chromosomes of Parents 1 and 2 is selected
- Children 1 and 2 receive genetic information of associated parent except for selected region of which they receive opposite parent’s genes

Mutation

- Usually quite low probability, .01-.1
- Element of individual's chromosome is randomly selected and changed
- In binary coding, this simply means changing a "0" to a "1" or a "1" to a "0"
- Another means of increasing the diversity of a population

Generations

- After population of individuals undergoes selection, crossover, and mutation, resulting population constitutes a new “generation” and the process is repeated
- Algorithm runs enough generations such that the solution converges to a global maximum
- Typically need 50-200 generations to converge

Advantages of GA-optimizers

- Do not depend on initial set of conditions
- Do not depend on local information such as derivatives
- Simple to understand and formulate
- Produce unusual and nonintuitive results

Ideal Solution Spaces for GAs

- Discontinuities
- Constrained parameters
- Large number of dimensions
- Many potential local maxima

Disadvantage and Implications

- Slow Convergence Time
- GA optimizers must evaluate every individual in a population over ~100 generations to converge to global maxima
- HFSS takes ~6 minutes for each antenna simulation

6 * 100 (population) * 100 (generations) =

60,000 minutes = 1000 hours = 41 days

Numerical Electromagnetic Code (NEC)

- Electromagnetic Simulator of wire structures based on Method of Moments (MoM)
- Offers fast, accurate, and reliable simulated results
- Simulation time for 100-wire segment : 20 sec.

$$1/3 * 100 * 100 =$$

$$3333.33 \text{ minutes} = 55.55 \text{ hours} = 2.3 \text{ days}$$

Antenna Design: Good Candidate for GA Optimization?

- Antennas have many dependent parameters that create nonlinear design problems
- In electromagnetic-design problems, “convergence rate is often not nearly as important as getting a solution”
- Solution space for antennas is vast and usually most of it is unexplored

… Maybe?

Crooked Wire Antenna

Linden and Altshuler

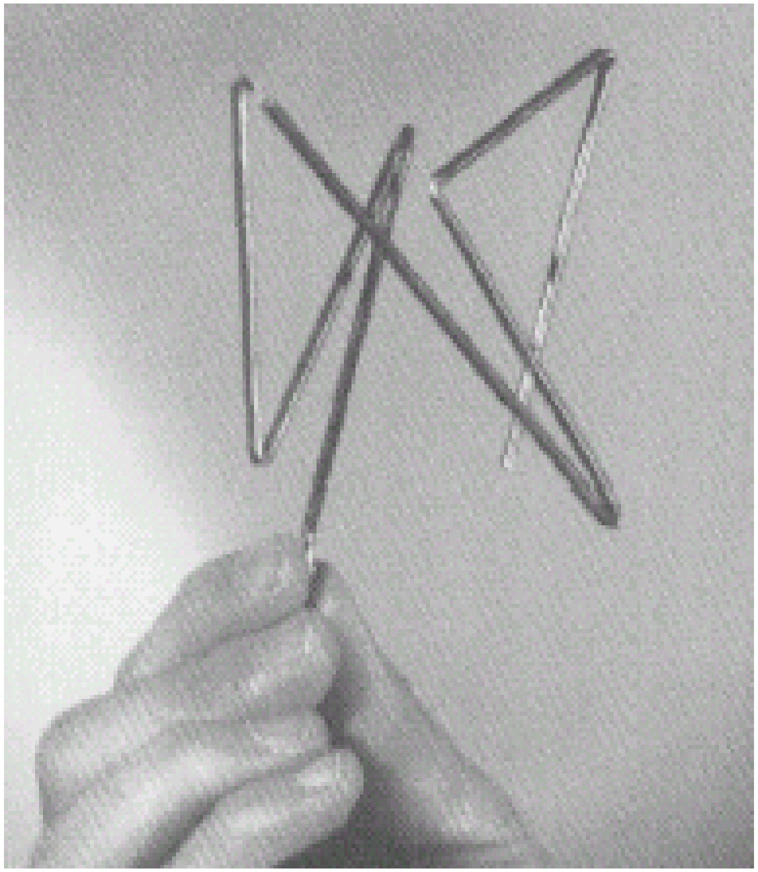
- Search for RHCP antenna that radiates over hemisphere with 7-wire antenna confined to .5 in cube
- **Gene:** 5-bits for each axis coordinate, 3 axis coordinates per point, 7 design points
- **Chromosome/Individual:** 5x3x7 = 105 bits

10010	01010	10001	11101	10101	10011	00110	10010	10111	11111	00010	10110
X_1	Y_1	Z_1	X_2	Y_2	Z_2	X_3	Y_3	Z_3	X_4	Y_4	Z_4

11000	00111	10110	00110	01011	10011	11001	10010	01101
X_5	Y_5	Z_5	X_6	Y_6	Z_6	X_7	Y_7	Z_7

Crooked Wire Antenna

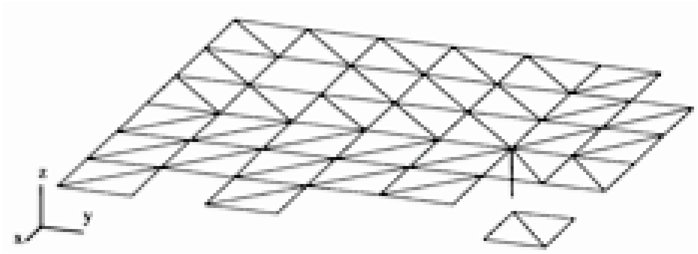
- Population: 500
- Crossover: 50%
- Mutation: variable, <8%
- Generations: 90

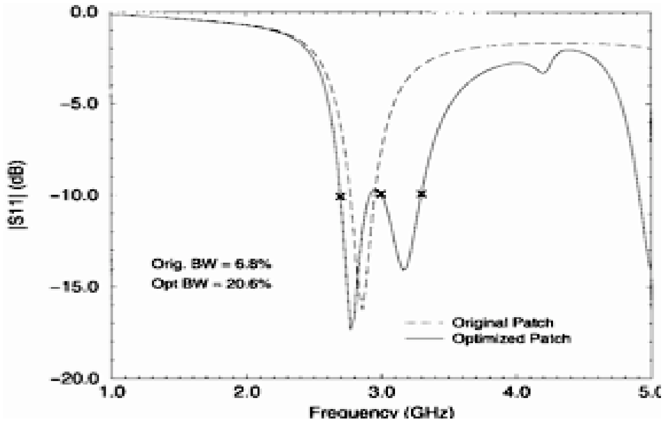


Broadband Patch Design

Johnson and Rahmat-Samii

- Gene: 1-bit string representing the presence or absence of a subsection of metal in the patch
- Chromosome/Individual: λ/2 square patch, fed by simple wire feed
- Population: 100
- Crossover: 70%
- Mutation: 2%
- Generations: 100



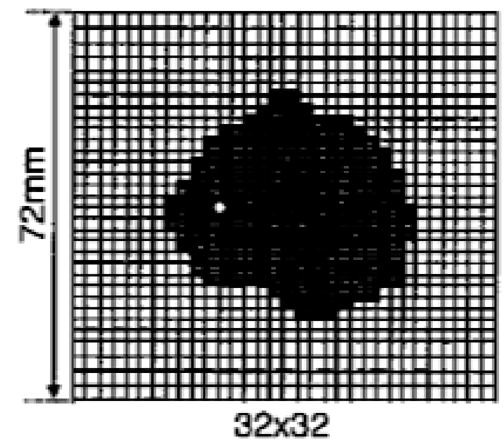


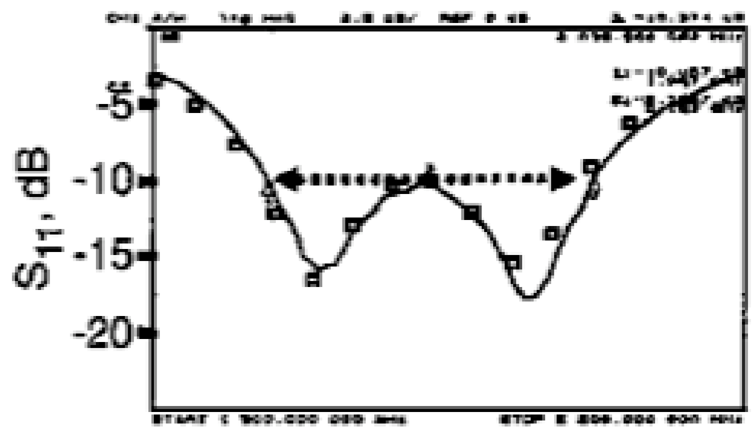
Non-optimized patch antenna BW: ~6%.
GA-optimized Patch BW: 20.6%.

Broadband Patch Design #2

Choo, et. Al.

- Gene: sub-patches were represented by either ones (metal) or zeros (no metal).
- Goal: broaden gain around 2Ghz by changing patch shape
- Optimized BW: 8%
- Regular: 2%
- Four-fold increase

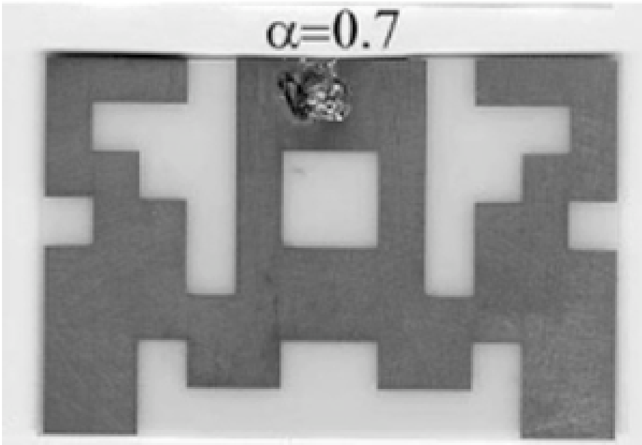




Dual-Band Patch Antena Design

Villegas, et. Al.

- **Goal:** dual-band patch antenna for 1.9 Ghz and 2.5 Ghz operation
- **Gene:** 1-bit string representing the presence or absence of a subsection of metal in the patch.
- **Individual:** 2D rectangular array of binary elements.
- **Population:** 260
- **Crossover:** 70%
- **Mutation:** 5%
- **Generations:** 200

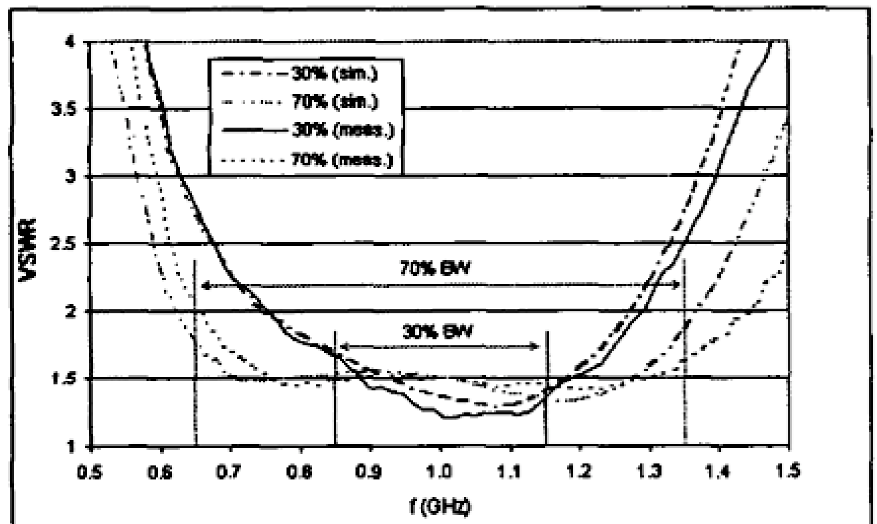


BW at 1.9 Ghz: 5.3%
BW at 2.4 Ghz: 7%

Compare GA-optimized BT and RBT Antennas, *Kerkhoff, et. Al.*

- **Gene:** The antenna height H and the flare angle α and feed height h_f (for RBT).
- **Chromosome/Individual:** Bowtie or reverse bowtie antenna with specified height H, flare angle α, and feed height h_f in the case of the reverse bowtie.
- **Population:** 60.
- **Crossover:** 50%
- **Mutation:** 2-4%
- **Generations:** N/A/

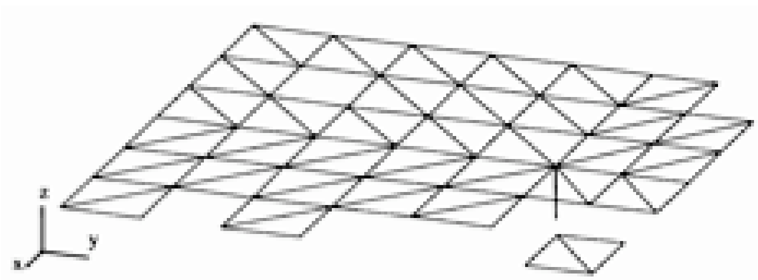
RBT could achieve 80% BW w/ smaller size than BT

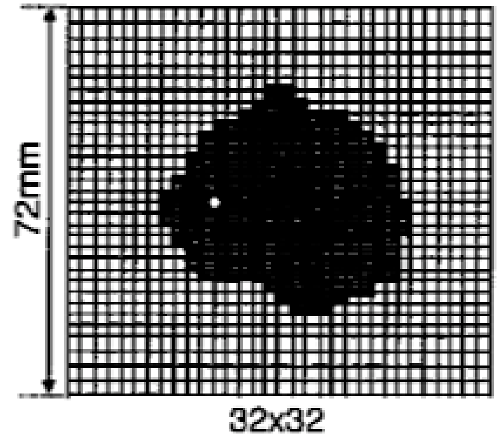


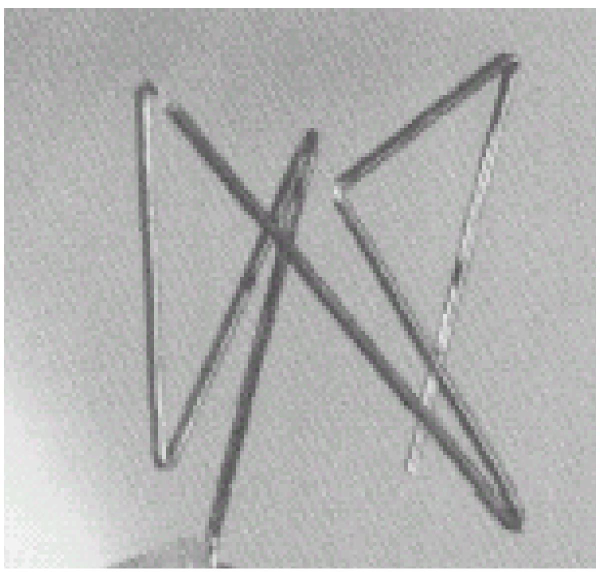
Measured and simulated results of GA-optimized RBT match

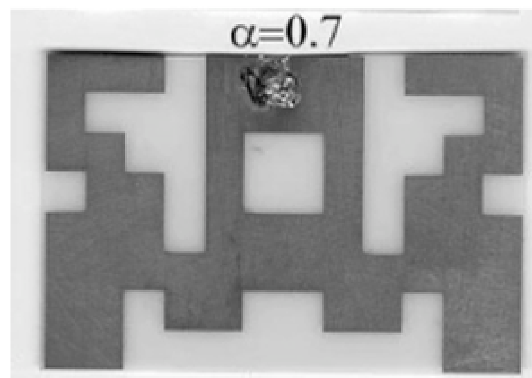
Study shows that genetic algorithms are effective in evaluating antennas, specifically broadband antennas

GA-optimized Antennas









GA-optimizers for RFID?

GA-optimizers for RFID?

Good for solution spaces with:

- Discontinuities
- Constrained parameters →
- Large # of dimensions
- Many potential local maxima

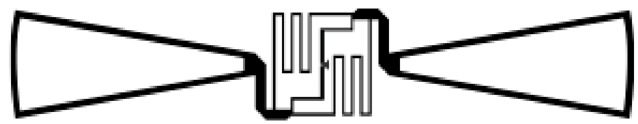
RFID Tag Constraints

- Size
- Cost
- Planar Configuration
- Polarization

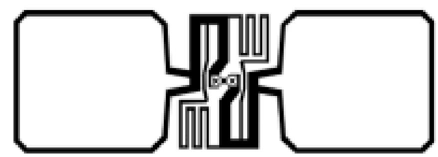
GA-optimizers for RFID?

Alien's "2x2"

Alien's "Squiggle"



"AD-612"



"AD-420"

Alien's "M"

Alien's "I"

"AD-220"

GA-optimizers for RFID?

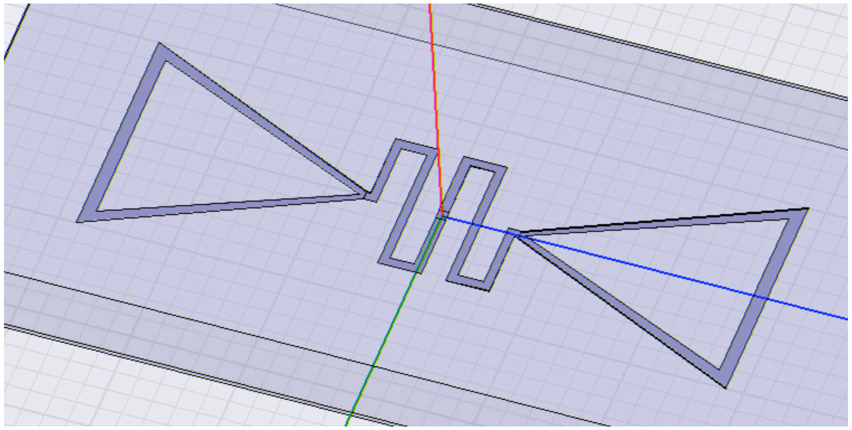
- Limitations of existing tags are limiting factor to RFID efficiency
- Tags are not efficient enough, small enough, or cheap enough
- Despite creative patterns, existing antennas are all intuitive and predictable-- based on traditional techniques-- limited to initial conditions and scope of designer's knowledge
- Antenna solution space far exceeds designer's notions

GA-optimized RFID Bowtie Antennas

- Optimized version of my bowtie
- Area limited to AD bowtie dimensions of 5.5 inx .98 in
- Genes: lengths of triangle height, triangle base, and squiggle
- Fitness function:

$$F = -G + C_1 * VSWR$$

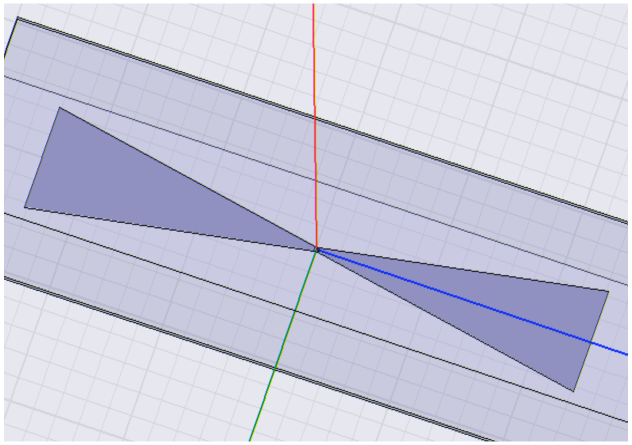
- Use NEC



GA-optimized RFID Bowtie Antennas

- Optimize full-metal bowtie by implementing patch chromosome method
- Gene is subpatch of metal with binary value
- Fitness function:

$F = -G + C_1*(VSWR) + M$



Questions? Suggestions?